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The application of the Italian Fire Code (IFC) to Battery Energy Storage Systems (BESS)

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The increasing in electrical energy production with renewable energy sources, due to their discontinuous and unpredictable availability, poses new problems to electrical grids managers.

One of these is the need to store energy when available, and to deliver it back to the grid when needed.

An increasingly widely adopted system is to use Battery Energy Storage Systems, commonly referred to as BESS, that are integrated high energy density systems, consisting in several battery racks composed by several cells connected in modules, including the battery management system (BMS) and all the ancillary systems like air conditioning and safety devices.
A number of battery construction technologies are available, among which those that provide the best performance are those based on Lithium-ion.
Lithium-ion batteries are used to provide energy for the greatest part of electronic devices like tablets, laptops, smartphone, electric bikes and so on, due do their high energy density and their tolerance to rapid charging-discharging cycles.
It’s worth noting that when we refer to Li-ion batteries, we’re actually referring to different types of Li-ion batteries are available, based on different technologies and materials; in this article we’ll not examine in detail the difference between batteries based on different technologies.

The potential dangers of lithium-ion battery energy storage systems (BESS) can generally be classified into several categories, namely fire and explosion risks, chemical risks, electrical risks, stranded energy risks, and physical risks. Among these, thermal runaway represents the most severe hazardous condition that can lead to significant consequences. Thermal runaway refers to an uncontrolled self-heating state within a lithium-ion cell, characterized by an exothermic reaction resulting in exceptionally high temperatures, the release of flammable and toxic gases, the ejection of dangerous debris and particles, as well as the generation of smoke and fire. Once thermal runaway initiates in one cell, it can propagate and spread to adjacent cells, modules, and potentially beyond, depending on the effectiveness of the protective measures in place to limit its spread. If thermal runaway continues to propagate, a substantial accumulation of flammable gas can occur, creating the risk of explosion or fire.

The fire risk assessment and the mitigation strategies

To prevent lithium-ion batteries from undergoing thermal runaway and to manage its consequences, various measures are typically implemented. These strategies aim to avoid the initiation of thermal runaway, handle the byproducts and impacts associated with it, and provide cooling to slow down the spread of the effects to other cells within a module or rack. The challenge in safeguarding a lithium-ion BESS lies in the fact that it presents a concurrent risk of both fire and explosion. Most fire suppression methods, such as sprinkler systems, are designed assuming the occurrence of ignition. However, if the ESS fails to ignite, the release of gases during thermal runaway can still pose an explosion hazard. Consequently, conventional mitigation strategies may face difficulties when it comes to protecting lithium-ion battery ESS, given the ever-evolving technology and designs, the unique hazards associated with thermal runaway, prolonged events, ill-defined protection objectives, and limited proven mitigation techniques.

When addressing the mitigation of hazards in lithium-ion BESS, it is crucial to carefully consider the formulation of protection objectives and the creation of holistic mitigation approaches that encompass prevention, impact management, and exposure management.

In Italy, according to local regulation, these goals are achieved by performing the Fire Risk Assessment (FRA) and selecting the proper mitigation strategies in accordance with the Italian Fire Code (DM 18/10/2019) that suggests the definition of a holistic fire safety strategy based on independent protection controls (preventive and mitigative measures) to be maintained during the life-cycle of the assets (Fiorentini & Dattilo, 2023). Approach has been conceived using techniques typical of the industrial risk domain (Crawley, 2020).

In order to perform the Fire Risk Assessment for an industrial BESS installation, the Bow-Tie methodology (Fiorentini, 2021) has been selected. This methodology has been integrated with LOPA (Layers of Protection Analysis) for a semi-quantitative preliminary risk screening in a workflow in line with the upmost recent SFPE guide to fire risk assessment (SFPE, 2023).

The bow-tie methodology is a risk management approach commonly used in various industries, including safety and hazard management. It provides a visual representation of the relationship between hazards, their causes, consequences, and the preventive and mitigative measures in place.

The bow-tie diagram takes its name from its shape, which resembles a bow-tie. It consists of three main elements: the left-hand side represents the causes or threats that can lead to a hazardous event, the knot in the center represents the event itself, and the right-hand side represents the consequences that can arise from the event. The diagram also includes two wings, one on each side of the knot, which represent the preventive measures on the left and the mitigative measures on the right.
On the left-hand side of the bow-tie, preventive measures are depicted. These measures are designed to reduce the likelihood of the hazardous event occurring. They can include safety protocols, engineering controls, training programs, or maintenance procedures aimed at preventing or minimizing the causes or threats.
On the right-hand side of the bow-tie, mitigative measures are shown. These measures are implemented to minimize the consequences of the hazardous event should it occur. They can include emergency response plans, protective equipment, evacuation procedures, or containment systems designed to mitigate the impacts and protect people, property, and the environment.
The bow-tie methodology is a valuable tool for visualizing and analyzing risks, understanding the relationships between causes, events, and consequences, and identifying the effectiveness of existing preventive and mitigative measures. It helps organizations develop comprehensive risk management strategies and enhance their understanding of hazards and their potential impacts.

Considering the preventive and mitigation barriers identified in the Bow-tie analysis conducted, it is possible to define a correlation between these barriers and the Strategies introduced by the Fire Prevention Code DM 18/10/2019.

In the specific case of the analysis carried out, the correspondence between the specific preventive/mitigative barriers considered and the fire-fighting strategies is given below:

Bow-tie barrier	**Fire safety strategy according to DM 18/10/2019**
Battery Management System	S.10 Fire safety of technological and service systems
Battery Management System (the BMS disconnects the affected batteries for temperature rise above the threshold due to chiller malfunction)	S.10 Fire safety of technological and service systems
Activities conducted under Permit To Work procedure	S.5 Fire safety management
Operational intervention with isolation of BESS following activation of overtemperature alarm	S.5 Fire safety management
Fire resistance characteristics of the barrier between containers	S.2 Fire resistance
Minimum separation distance between the various BESS	S.3 Compartmentation
Smoke ban	S.5 Fire safety management
Housekeeping	S.5 Fire safety management
Hazardous substances confined in designated areas adequately spaced from BESSes	S.3 Compartmentation
Gas detection alarm activation	S.7 Fire detection and alarm
High cell temperature trip (cell level)	S.10 Fire safety of technological and service systems
Thermal runaway trip (cell level)	S.10 Fire safety of technological and service systems
Rack switch fail-to-trip (rack level)	S.10 Fire safety of technological and service systems
Inverter/charger fail-to-trip (supervisor level)	S.10 Fire safety of technological and service systems
Extraction fan activation	S.8 Smoke and heat control
Fire detection alarm activation	S.7 Fire detection and alarm
Automatic aerosol fire alarm activation following fire detection and simultaneous stop of HVAC system and extraction fan	S.6 Fire control
Automatic aerosol fire extinguishing system activation following fire detection	S.6 Fire control
Activation of water fire extinguishing system (dry pipe) following intervention of tanker truck alerted by Emergency Manager/hydrant connection	S.6 Fire control
Fuse	S.10 Fire safety of technological and service systems
Use of UL 9540A certified cells reduces thermal runaway	S.10 Fire safety of technological and service systems
Flame-retardant and self-extinguishing cables	S.10 Fire safety of technological and service systems
Internal safety distance in accordance with DM 15/07/2014	S.3 Compartmentation

Electrical protections that isolate the equipment in milliseconds	S.10 Fire safety of technological and service systems

The presence of this parallelism allows for the identification and contextualization of the key design characteristics within the analysis. These characteristics are aimed at meeting fire safety requirements, and their assessment, in terms of both effectiveness and efficiency, can be addressed during the subsequent in-depth project analysis as planned.

The bow-tie application to BESS fire and explosion risk assessment (FRA)

In Figure 1 a typical bow-tie diagram depicting the application of the Italian Fire Code strategies to a BESS is reported; in order to reduce the diagram size some barriers elements are shown as grouped (collapsed).

As reported in the right side of Figure 1, four scenarios have been considered in the FRA:

1) Uncontrolled fire confined to a single BESS container;
2) Uncontrolled fire involving other BESS containers;
3) Explosion and consequent projection of fragments;
4) Fire controlled by dry pipe activation and subsequent contamination (environmental impact).

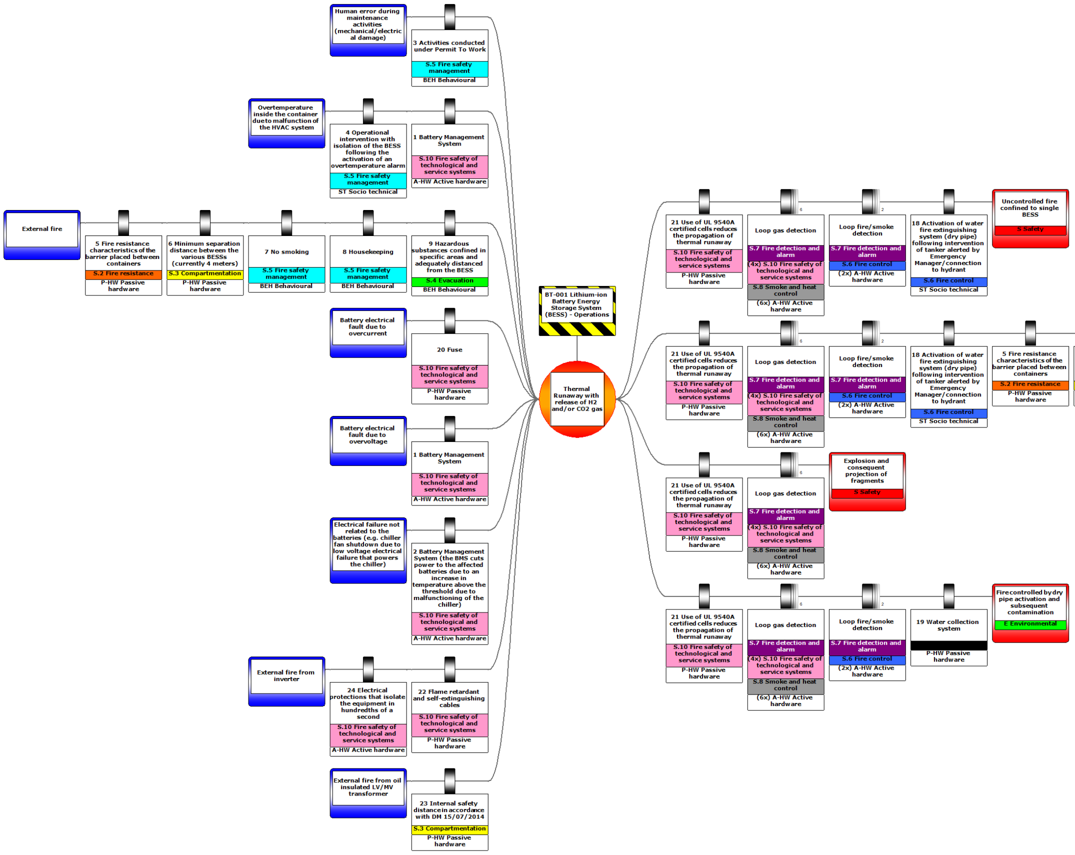

Figure 1, typical bow-tie diagram for BESS installation (collapsed)

Looking at Figure 1, we can see that on the left side barriers are interposed between the initiating events and the top-event, while at the right side they're interposed between the top-event and the scenarios.

Taking as example Scenario no.1, “Uncontrolled fire confined to a single BESS container”, is mitigated by four barriers:

- Use of UL9540A certified cells that reduces the propagation of thermal runaway (Italian Fire Code Strategy S.10 regarding the various triggering equipment for process safety);
- Gas detection loop that activates battery or electrical systems isolation or shutdown (involving Strategies S.7 regarding detection systems, S.8 regarding smoke control system and S.10);
- Fire/smoke detection loop that activates automatic fire suppression systems and triggers emergency response (Strategies S.6 regarding active fire protection systems and S.7);
- Activation of water fire extinguishing system (dry pipe) following intervention of tanker alerted by Emergency Manager / connection to hydrant (Strategy S.6).

Some of those barriers should be considered safety instrumented functions, therefore, according to IEC61508 and IEC61511 standards on functional safety, their risk reducing factor and their probability of failure on demand should be defined on the basis of functional safety performance requirements (Fiorentini & Cancelliere, 2023).

References

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